Driving Adoption of Demand-Responsive Commercial Lighting with a Clarified Value Proposition: Site Level Energy Savings and Cost-Benefit Analysis

Authors:

Brian F. Gerke, Jennifer Potter[1], Peter Schwartz, Alastair Robinson, David Jagger[2], Jasmine Shepard[2], Teddy Kisch[2], Adel Suleiman[3]

[1]Hawaii Natural Energy Institute

[2]Energy Solutions

[3]California Energy Commission

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ABSTRACT

Commercial lighting represents a significant potential source of demand response (DR) for the electrical grid, via traditional load shedding and also via rapid-dispatch ("fast-DR") ancillary services when DR is enabled by networked lighting controls (NLCs). Since 2013, California Title 24 building code mandates DR-capable lighting in certain circumstances. Despite the significant opportunity and regulatory push, DR-enabled lighting is installed and enabled in a relatively small number of buildings because most building owners do not see a strong value proposition from DR-enabled lighting. While NLCs can support DR enablement by providing additional capabilities that deliver value to the customer such as reduced energy bills, optimized space utilization, and increased revenue, these co-benefits from NLCs are not well quantified. This paper undertakes a detailed analysis of lighting DR resources and energy-related co-benefits for commercial buildings in California. Using over 100,000 individual hourly load profiles, we forecast the potential DR resources that could be available from commercial lighting in 2025. We also estimate the revenues available from participation of these DR resources in energy markets. Combining these results with field-study estimates for NLC installation costs and energy savings, we perform a detailed accounting, by building type, of the site-level costs and energy-related co-benefits arising from DR enablement with NLCs. In many cases, the energy savings alone can deliver significant net value to the site, strongly justifying the adoption of NLC-enabled DR. A companion paper considers the additional non-energy benefits, which can be even larger than the energy benefits.

Introduction

NLCs are among the many rapidly evolving technologies that utilize wireless communications, embedded sensors, data analytics and controls to optimize building systems in real time. The high levels of insight and controllability offer not only opportunities to save energy, but also to improve space utilization and occupant satisfaction, as well as to develop dispatchable building loads for DR grid services. Because of this new functionality, the lighting controls market is shifting, and energy savings are becoming a smaller piece of the technology's overall value proposition. This shift adds complexity to what was previously a simpler analysis, comparing system costs to energy savings to promote adoption of traditional lighting controls.

In California, a rapidly expanding portfolio of intermittent renewable power generation means that increased DR is likely to be of significant value to the grid in the future, with commercial lighting representing a substantial potential DR resource (Alstone et al. 2017). California's Title 24 building energy codes require DR-capable lighting in some cases; however, uptake of DR-capable lighting controls has been limited (Jackson 2017), due in part to the aforementioned complexities in expressing the value proposition.

In a recent study (Schwartz et al. 2018) for the California Energy Commission (CEC), we developed a valuation framework for DR-enabling NLCs, setting the system and operating costs against a full array of benefits including energy cost savings, revenue from DR participation in energy markets, and a variety of non-energy benefits (NEBs) arising from improved lighting control. In this paper, we focus on the energy part of the equation, developing a detailed model to forecast the costs and energy-related savings associated with DR-enabled NLCs in office and retail buildings, for each of the three California investor owned utilities (IOUs). A companion paper to this one (Sanders et al. 2018) presents a detailed framework for valuation of the NEBs, along with a strategy for using NEBs to help drive adoption.

Our modeling takes a data-driven bottom-up approach, based on measured hourly consumption data for hundreds of thousands of utility customers, as well as cost data from real-world NLC installation projects. In the next section, we begin by describing the specific DR resource categories that can be supported by NLCs. The Methodology section describes our techniques for modeling the potential DR resource and energy savings available from NLCs, as well as our approach to estimating NLC system costs. In the Results section, we present a detailed comparison of costs and benefits for different building sizes and occupancies across the different IOU service territories, as well as estimates of the total potential DR resource and energy savings that are available from adopting NLCs for these buildings.

Demand Response Service Types and Enabling Technologies for Lighting

Demand Response Service Type Definitions

This paper considers DR services and technologies for commercial lighting within the framework established for the California Public Utilities Commission (CPUC) by Phase 2 of the California Demand Response Potential Study (Alstone et al. 2017[1]; see also Alstone et al. 2018 in these proceedings for a summary). The study considered possible modes of operation for DR in the context of the future grid in 2025 and identified several different DR "service types" or broad categories of operation. Two of these service types are relevant for the lighting end use[2]:

- ***Shed*** is the traditional DR service type: occasional load curtailment to provide peak capacity and support the system in emergencies. From the perspective of the grid, *Shed* resembles a generation capacity resource. Lighting can provide *Shed* service by reducing output to lower levels that are still sufficient for ordinary operations.
- ***Shimmy*** dynamically adjusts loads at timescales ranging from seconds up to an hour. From the grid perspective, *Shimmy* resembles frequency regulation or load-following ancillary services (AS). NLCs can provide *Shimmy* service by modulating lighting levels upwards or downwards on short (5-15 second) timescales by imperceptible amounts.

Demand Responsive Lighting Technologies

DR-enabling technology can be categorized into three general components, each of which is required for reliable DR operations and market participation: control infrastructure, communication infrastructure, and measurement infrastructure. The infrastructure components deployed at a particular site define the costs for the system and determine the DR service types that the lighting system can provide. In this study, we modeled communication and measurement costs and performance using identical assumptions as those detailed in the CA DR Potential Study. To model lighting control costs and performance, we focus on three types of NLCs:

- **Luminaire-level** systems, with granular digital controls managing individual luminaires;
- **Zonal** systems, involving sets of luminaires controlled as a group; and

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[1] Hereafter referred to as the CA DR Potential Study.

[2] The CA DR potential study also considered DR service types called *Shift* and *Shape. Shift* captures the potential for shifting loads throughout the day, which is generally not possible for commercial lighting loads (see Gallo et al. 2018 for an overview of *Shift* DR). *Shape* refers to persistent load reshaping that is not dispatchable by the grid operator, which is outside of the area of our focus in this analysis.

- **Standard** practice lighting systems that just meet CA Title 24 requirements.

We assume that zonal and luminaire-level lighting systems are capable of providing *Shed* and *Shimmy* Services, while standard lighting controls can only provide *Shed* since they may not be sophisticated enough to permit rapid and continuous dimming (Wei et al., 2015).

Methodology

The DR-Futures Model For Estimation of Demand Response Potential

This study employs the bottom-up modeling framework for DR capabilities and availability that was developed for the CA DR Potential Study. The framework leverages detailed data on hourly electricity consumption in calendar year 2014 for hundreds of thousands of IOU customers, which was provided for the CA DR potential study. The first step for estimating DR resource availability is to group customers into similar cohorts, called "clusters," based on building type, energy consumption, peak demand, and geographical location. Each cluster's aggregated load shape is representative of consumption for a particular customer subgroup, at a level of aggregation that preserves the anonymity of individual customers. The load shapes are disaggregated into constituent end uses, and these end-use baseline load shapes are forecasted to the study year of 2025.

The DR Futures model is divided into two core analytical capabilities:

- **LBNL-Load** is an end-use load-forecasting model based on IOU-provided demographic and hourly load data for a cross-section of IOU customers. Using these data, we developed approximately 2,700 customer clusters, with hourly end-use load forecasts for each, over a full year.
- **DR-Path** is a DR capability analysis model that estimates the potential DR resource across a diverse set of future technology pathways. Each pathway represents the DR available from a particular enabling measure in a particular cluster, considering the predicted end-use load (from LBNL-Load), technology capabilities and costs, market design parameters and expected customer participation rates.

The final output of the modeling is an estimate of the DR supply curve—i.e., the available amount of DR capacity (the kW of load that can provide *Shed* or *Shimmy* service on average throughout the year), for each cluster and end use, at a particular levelized cost of procurement.

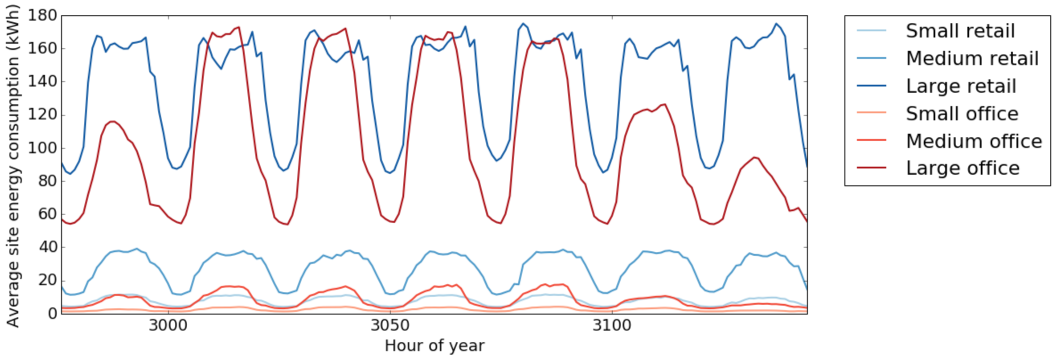

Figure 1: Example forecasted 2025 site-level lighting load profiles each of the building occupancies that are modeled explicitly in the DR-Futures framework for this study. Curves show one week of lighting load for a selected set of clusters drawn from LBNL-Load.

In general, the amount of available DR is higher at higher procurement costs, since (1) better-performing technologies can be purchased and (2) better incentives can be offered to recruit customers to participate. However, there is always a *maximum* amount of available DR for each cluster and end use, above which there are no further technological or program improvements that can be made. In this study, we compute this maximum value as an estimate of the total DR resource that is potentially available for the commercial lighting end use.

Commercial lighting load was explicitly disaggregated in LBNL-Load for clusters representing office and retail buildings. The clustering further subdivides these building types into small, medium or large site sizes if their peak demand is less than 50 kW (small), between 50 and 200 kW (medium), or greater than 200 kW (large), respectively. (This characterization is consistent with IOU practices for assigning rates and demand charges.) With the disaggregated load shapes, we can proceed to estimating the DR potential, and the associated costs and benefits for these building occupancies and site sizes.

Developing the Lighting Load Shapes

To determine the eligible load for DR participation, we used the cluster load profile forecasts by end use that were developed during the CA DR Potential Study, generated by disaggregating actual customer hourly load data from 2014. The lighting load profiles were disaggregated based on the California Commercial End Use Study (CEUS) load-profile dataset (CEC 2006). To account for the large time difference between the 2006 CEUS and our 2014 input data, we applied a 20% downward correction to the CEUS lighting profiles to capture the impact of statewide lighting retrofit programs that replaced T12 with T8 florescent fixtures, resulting in ~20% lower energy intensity for commercial lighting relative to the CEUS estimates. We then forecasted the growth of each end use to 2025, assuming no additional DR, under the "mid" scenario for additional achievable energy efficiency (EE) estimated in the 2014 California Energy Demand Forecast (CEC 2014). (Notably, this scenario does not include a transition to LED technology, which was considered an emerging technology in 2014. As discussed below, we assume that DR-enablement for lighting includes an upgrade to LED lighting.)

Figure 1 shows example average site-level lighting load profiles for a selected set of clusters, forecasted to 2025, for the various building occupancy types and site sizes modeled in this study.

Cost Estimates for DR Lighting Enablement

We used two approaches to estimate project costs for NLC installations: modeling NLC project costs based (1) on a set of standard building prototypes, and (2) project invoice data from completed NLC projects. Outreach to industry representatives yielded cost estimates for eight distinct NLC system products. To standardize across the product offerings, each estimate was based on sample CEC prototype buildings with pre-specified floor areas, coupled with fixture densities based on industry practice. Secondly, we analyzed project invoice data from 23 NLC projects completed from 2014 to 2017, separating costs into fixture and controls components.

Table 1 provides the average cost per square foot of an NLC system for office and retail buildings, broken out by materials and labor for fixtures and controls. As shown, NLC project costs are generally consistent across building types, though small retail is slightly higher due to a higher fixture density. Notably, the controls costs are generally smaller than the fixture costs.

Table 1: Average Fixture and Control Costs (Dollars per square foot)

Building Size	Building Type	Average Fixture Materials Costs	Average Fixture Labor Costs	Average Controls Materials Costs	Average Controls Labor Costs
<10,000	Office	\$2.07	\$1.26	\$0.68	\$0.31
	Retail	\$2.87	\$1.59	\$0.40	\$0.23
10,000-100,000	Office	\$1.83	\$0.96	\$0.34	\$0.40
	Retail	\$1.50	\$1.07	\$0.35	\$0.19
>100,000	Office	\$1.81	\$0.77	\$0.29	\$0.23
	Retail	\$1.46	\$0.71	\$0.21	\$0.10

Technology Performance Assumptions

For each advanced lighting system, we estimate the load reduction that can be obtained from each control technology for each service type. Importantly, we have assumed that all DR-capable lighting installations will include an upgrade to LED lighting technologies. These lighting upgrades ultimately reduce the absolute amount of DR that can be obtained from lighting systems; however, incentivizing upgrades to LED systems with NLCs would result in more DR capable lighting systems throughout CA. On top of this overall load reduction, we assumed that our three categories of lighting controls could achieve different levels of performance in response to DR signals based on the different levels of control they enable. Specifically, we assumed that standard controls can reduce load by 20% during *Shed* DR events but cannot participate in *Shimmy*; that zonal controls can achieve 35% reduction for both *Shed* and *Shimmy*; and that digitally addressable luminaires can achieve load reductions of 65% for both of these service types (e.g., by turning off some luminaires completely in unoccupied areas).

Additionally, the CA DR Potential Study defined three feasible DR market and technology trajectory scenarios: Business-as-usual, Medium, and High, representing different trajectories in cost reduction and performance improvement for DR technologies over time. Here, we report all findings in the Medium scenario. The scenario defines multipliers on the DR costs and performance in 2025, relative to a 2014 baseline. Rational caps on performance are enforced (so that, e.g., a site cannot *Shed* more load than what is under control, regardless of the performance multiplier). The 2025 CA DR Potential Study also considered different weather scenarios, but these have no effect on the lighting load forecasts, so we neglect them here.

Economic Valuation and for Demand Responsive Lighting

Cost Perspective. When defining DR technology systems' costs, we present the costs and benefits from the perspective of enabling a single site with DR technology. From this perspective, the associated costs include the costs of installing DR-capable lighting fixtures and controls, and any associated financing costs. We neglect costs that would accrue to the utility or aggregator, such as paying for incentives, program administration, or marketing, since these would be used as tools to strengthen the value proposition developed herein, so their proper amounts should be informed by the results of this study. As a result of enablement at the site, the benefits include a revenue stream from wholesale energy-market participation, as well as energy-savings co-benefits arising from the more efficient lighting system. Throughout, the costs and benefits are presented in levelized terms—i.e., as the average annual present value. To clarify the split between initial price and financing costs, we report these costs separately, with the levelized purchase price being simply the price divided by the system lifetime, while the levelized financing costs represent the present value of interest payments on the initial cost, amortized over the technology lifetime using a 7% cost of capital.

DR Lighting System Costs. For each of the lighting control systems, we estimate the initial up-front enablement costs for a customer site. The costs include device costs and labor costs for installation, as well as the costs of site-level DR-enabling hardware for communications and telemetry (for details, see Alstone et al. 2017). To apply these costs to a range of different sites, we convert the site-level estimates into a cost per kW of DR-enabled load ($/kW), as follows.

First, we estimate the average square footage for each building size and occupancy type and calculate the average cost per square foot ($\$/ft^2$) for each lighting control system[3]. Second, we derive the average amount of load shed expected in a DR event by multiplying CEUS estimates of non-coincident peak lighting load (corrected to account for a transition to LED technology) and the fractional *Shed* potential for each lighting DR control technology to yield the kW per square foot of DR available (kW/ft^2). Finally, we combine the cost and load-shed results to yield a cost per kW of enabled DR for each building type ($/kW). We have borrowed this accounting framework for the costs of enabling technology from Piette et al. (2015).

DR Sources of Revenue. DR services are able to receive revenue by participating in CAISO wholesale energy markets. In this study, we assumed that *Shed* services participate in the energy market and receive resource adequacy (RA) payments for providing reserve capacity, while *Shimmy* services participate in the AS market. Hourly prices for the energy and AS markets quantified in this study are obtained from a PLEXOS simulation run by CAISO based on the CPUC's 2014 Long-Term Procurement Planning scenario (CPUC 2013).

Results for this study are aggregated to annual values, and therefore, assumptions must be made for the dispatch frequency and timing of DR resources. As discussed in the CA DR Potential Study, *Shed* DR energy market revenue is calculated as the revenue earned in the top 250 net load hours of the year, weighted by the likelihood of a *Shed* event in each hour. We assume that *Shimmy* services, by contrast, are needed during all hours of the year. We assume that the site participates in the relevant AS market whenever its forecast market price is nonzero.

[3] It is important to note that, while luminaire-level and zonal controls can provide both *Shed* and *Shimmy*, *Shimmy* involves an additional communication and telemetry expense.

At those times, the potential market payment to the site is equal to the total load that can provide *Shimmy* service, multiplied by the market price. Summing this product over the full year yields a maximum annual ISO market revenue for participating in *Shimmy* markets.

Energy Cost Savings Co-Benefits of DR Lighting Technologies. For certain end uses, the same technologies or device upgrades that enable DR (e.g., smart thermostats, building EMS, or, in the case of our study, NLCs) produce other benefits by improving building performance (Goldman et al., 2010). These economic benefits are referred to in this study as "co-benefits." In practice, co-benefits could be realized through customer energy bill savings or from NEBs that yield improved comfort or convenience for occupants. In this paper, we consider the energy-savings co-benefits for NLCs, as these are the most straightforward to calculate in our modeling framework. We briefly discuss the methodology for calculating these co-benefits below, and we fold them into our calculation of the costs and benefits of DR enablement for lighting. A separate paper in these proceedings (Sanders et al. 2018) considers NEBs, which are generally more challenging to measure but may be substantially larger than the energy benefits.

The cost savings associated with energy savings in the commercial sector depend strongly on the hourly load profile of the end use involved, since most commercial customers in California pay time of use (TOU) rates that may have a high discrepancy between peak and off-peak periods. Thus, to estimate the energy cost savings associated with DR-enabled lighting systems, we first developed an hourly average commercial electricity rate for each of the California IOUs, based on published 2017 rate schedules, accounting for daily TOU variations, as well as seasonal changes and differences between weekday and weekend/holiday rates. Multiplying this hourly electricity rate by the forecast site-level lighting load profile for each cluster, and summing over all hours, yields a baseline annual site-level cost for lighting energy consumption, prior to any savings arising from adoption of LED or NLC technologies. To this annual cost, we then apply an adjustment to account for an annual increase in electricity rates, which we assume to be 3%/yr in inflation-adjusted terms for California. This escalation applies in each year from 2017 through 2025, and then accrues, with appropriate discounting, over a 15-year technology lifetime to yield a levelized annual electricity cost for installed systems in 2025.

We can then apply a series of multipliers to this baseline energy consumption to compute the estimated site level energy savings in each cluster. First, we assume that adoption of LED lighting yields a 50% reduction in lighting energy intensity, relative to the baseline forecast, so we assume LED adoption yields a 50% energy-cost savings. On top of this, a recent study by the DesignLights Consortium of NLC performance (Kisch et al. 2017) estimates that NLCs yield energy savings of 44% and 63% in retail and office buildings, respectively. To calculate the site-level energy cost savings from NLCs in each cluster, then, we apply the appropriate multiplier to each cluster's remaining energy costs after accounting for the LED savings.

Results

The modeling described in the Methodology section yields site level costs and benefits for each of the commercial office and retail clusters. To produce final aggregated results by building type and IOU, we average the costs and benefits, weighting by the number of customers in each cluster, for all clusters in a particular segment of interest (e.g., medium retail buildings in a particular utility service territory). To compute the total potential DR resource and incremental energy savings, we sum the available DR and total cluster energy savings across the customer segment of interest. These aggregated results are presented in this section.

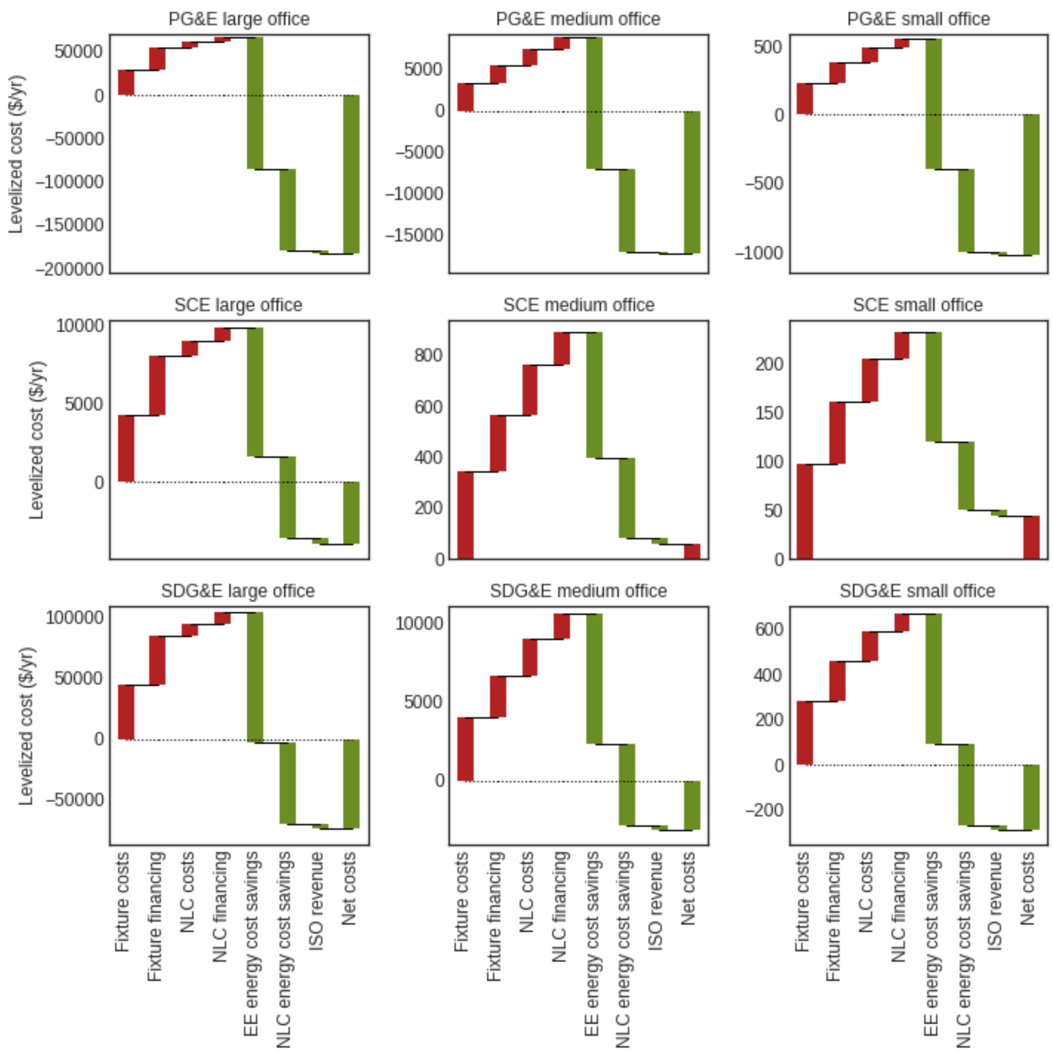

Figure 2: Waterfall diagrams showing the levelized annual costs and energy-related benefits of a DR-enabled lighting system installation, in office buildings of three different size categories in each of the California IOU service territories.

Figure 2 and Figure 3 display the site-level levelized costs and energy-related benefits from installing a DR-enabled lighting system in different building categories (small, medium and large office and retail) within each of the California IOU service territories. The cost and benefit results are presented as waterfall diagrams, displaying costs as positive red bars that incrementally build up the total cost, while benefits are shown as negative green bars. The aggregated benefit subtracts from the aggregated cost to yield a total “energy-only” (i.e., exclusive of NEBs) net cost, shown with a heavy outline at the far right of each panel. Negative net costs indicate that NLCs can yield a net benefit to the site operator from energy-related revenue streams alone. Costs include the levelized up-front costs of purchasing and installing new lighting fixtures and NLCs, as well as the related financing costs (assuming a 7% cost of capital), as described the Methodology section. The benefits in this analysis are limited to the readily quantifiable energy-related benefits of the installation, whose calculation is described in the Methodology section. These include the annual reduction in energy expenditures arising from

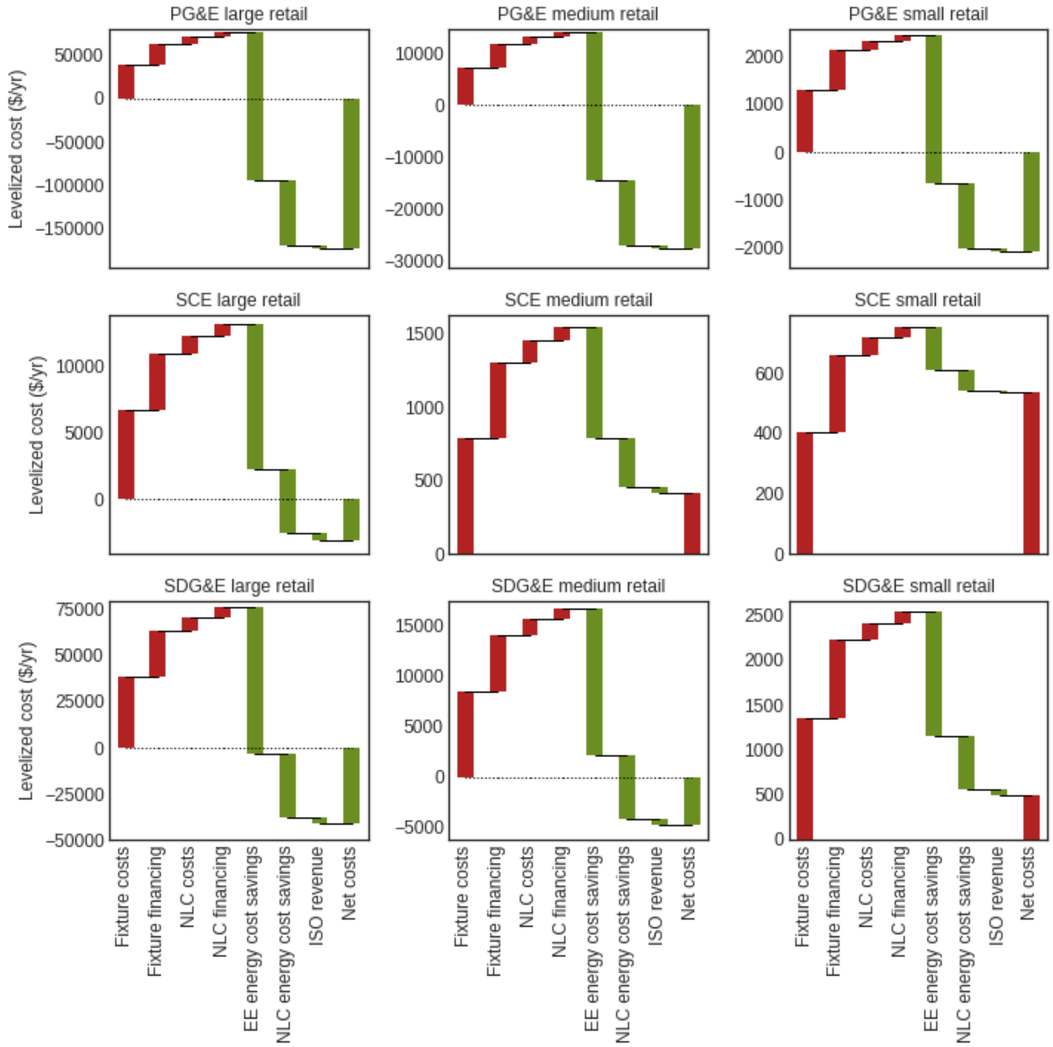

Figure 3: Waterfall diagrams as in Figure 2, for retail buildings in the three California IOU service territories.

static EE savings (i.e., LED savings over a fluorescent baseline) and from NLC operation, as well as the maximum available revenue from participating in ISO markets.

The figures show that the energy-only cost-effectiveness of DR enabled lighting systems varies substantially depending on building size and service territory. In general, such systems are more cost effective for larger buildings than for smaller, and for offices than for retail sites, across all service territories. In PG&E's service territory, where commercial retail electricity rates are relatively high (especially on peak), there is a substantial net benefit across all building sizes and types, and DR-enabled systems can generally be justified based on the static EE savings alone. In SCE's service territory, by contrast, where electricity rates are lower, the cost-effectiveness of DR lighting systems depends strongly on the building size, with a net benefit for large buildings only. In this case, the value proposition for small and medium buildings would likely need to rest on the NEBs, rather than the energy-related benefits. The results for the SDG&E service territory are intermediate between these two cases.

Notably, the available revenue from ISO markets is always small relative to the system costs and the energy cost savings. This suggests that the primary energy-related value (exclusive

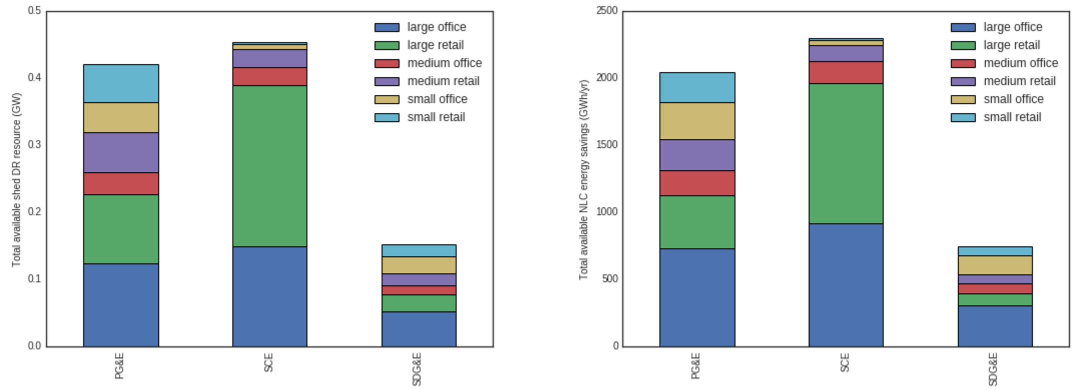

Figure 4: (Left) The total *Shed*-type DR resource (GW) that would be enabled during a typical *Shed* DR event if NLCs were installed universally in California office and retail buildings, by IOU service territory and building size. (Right) The total energy savings (GWh/yr) that would be achievable with these same NLCs.

of NEBs) for DR-enabled lighting systems comes from the energy savings that can be achieved with or without DR participation. It may therefore be important to develop additional strategies to encourage participation in DR programs, once DR-enabled technologies are adopted.

Using the DR-Futures model, we can also estimate the ***Shed*** and ***Shimmy*** resources that could be provided by DR-enabled NLC systems in California office and retail buildings. Figure 4 (left panel) shows the total ***Shed***-type resource that could be enabled by installing NLCs in all such buildings, broken down by IOU and building size. In aggregate, the NLC-enabled ***Shed*** resource amounts to 1 GW of DR capacity on average when ***Shed*** is likely to be needed. Both the breakdown and the absolute resource size are similar for the ***Shimmy***-type products.

We can also estimate the total possible energy savings that installation of NLC systems could provide. Figure 4 (right panel) shows this savings potential, broken down by building type and service territory. These savings are the additional dynamic savings available from operating DR-enabling NLCs, assuming that all buildings have already been upgraded to LED lighting. The aggregate potential savings are enormous, amounting to roughly 5 TWh/yr.

In Figure 4 it is worth noting that large buildings are the dominant source of both DR and energy-savings potential from NLC adoption in California. These are also the buildings which have the clearest energy-only value proposition for NLCs. Large commercial buildings have also historically had a much higher rate of DR participation than smaller buildings, so these buildings may be a particularly attractive target for future lighting DR programs.

Conclusion

We have performed a detailed, bottom-up analysis of the site-level costs and energy-related benefits, as well as the potential DR resources and aggregate energy savings, arising from installing DR-enabled NLCs in commercial office and retail buildings in California, as of 2025. Our model for the DR potential and energy benefits is built on detailed consumption data for hundreds of thousands of individual customers; coupling this with cost data derived from real installation projects yields a highly realistic accounting of the costs and energy benefits associated with NLCs. With our detailed estimate of the DR resources, we can augment the typical EE-focused analyses for lighting control systems with the additional revenue streams associated with energy-market participation, to yield a fuller accounting of the energy benefits.

We find that, for many building types (particularly large buildings and those in the PG&E service territory), installation of NLCs can be easily justified in a cost-benefit sense, based on the EE-driven savings alone. The potential DR revenue streams are small by comparison to the EE benefits and are unlikely to add significantly to the NLC value proposition. We also find the potential for significant energy savings (roughly 5 TWh/yr) and DR resources (roughly 1 GW of *Shed* DR capacity) arising from installation of NLCs in California retail and office buildings.

To assess the value proposition for NLCs in building types in which EE savings alone cannot justify NLC installation (such as small and medium sites in the SCE service territory), it will be important to also consider the various NEBs that NLCs can provide at the site and value these as quantitatively as possible. A separate paper in these proceedings (Sanders et al. 2018) develops a framework for NLC NEB valuation.

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